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Experimental Magnetohydrodynamic Turbulence Investigations

16 AUGUST 1962

Prepared by E. B. TURNER
Physical Research Laboratory

Prepared for DEPUTY COMMANDER AEROSPACE SYSTEMS
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
Inglewood, California

LABORATORIES DIVISION • AEROSPACE CORPORATION
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EXPERIMENTAL MAGNETOHYDRODYNAMIC TURBULENCE INVESTIGATIONS

by
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AEROSPACE CORPORATION
El Segundo, California

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ABSTRACT

Previous investigations of MHD turbulence are reviewed briefly, and a short description of the apparatus, a stabilized linear pinch device, is presented. Improvements in the frequency response of the magnetic probes and RC integrators and modifications to the design of the high-pass filters are discussed. The following experimental results obtained during the recent six-month period are presented: 1) Autocorrelation measurements have been performed on a set of Kerr cell photographs of the pinch to determine the wavelength of the instabilities. 2) Promising results have been obtained using an x-y oscilloscope to determine the degree of correlation between signals from magnetic probes separated by varying distances. 3) Alfvén wave propagation of the magnetic field fluctuations was observed by the phase shift between two probe signals. 4) Some analyses have been made of the rms values of * ~~B, $\dot{B}$, and $\ddot{B}$,~~ and the maximum frequency of the turbulence has been determined. 5) High-quality Kerr cell photographs of the pinch have been taken on color film, using a new Kerr cell with a fluid which transmits the entire visible spectrum. The need for automatic data reduction techniques and for digital computer processing of data is also discussed.

TABLE OF CONTENTS

FIGURES

I. REVIEW OF PAST WORK

The experimental apparatus used for this research is described in Reference 1. It is essentially a stabilized linear pinch device similar to the Columbus S-4 apparatus at Los Alamos with which Burkhardt and Lovberg (Ref. 2) detected fluctuations in the magnetic field. These high frequency fluctuations were thought to be caused by magnetohydrodynamic (MHD) turbulence. Kovásznay (Ref. 3) while a consultant to the Physical Research Laboratory at Space Technology Laboratories, developed an elementary theory for the MHD turbulence to explain the anomalous decrease in gross conductivity of the plasma which was found to occur at about the same time as the fluctuations.

The present apparatus was constructed in the Physical Research Laboratory* for the purpose of making a more systematic study of the MHD turbulence appearing in the linear pinch. Experimental studies have now been in progress for about one and a half years. Some characteristics of the pinch device are:

1) 85 μf capacitor bank usually charged to 15 kv
2) 5-in. ID ceramic or glass discharge tube
3) 24-in. distance between electrodes
4) initial longitudinal magnetic fields of up to 4000 gauss
5) typical half-cycle period of 12 μsec
6) typical maximum current of 220,000 amp.

In order to better understand the behavior of a linear pinch, many Kerr cell photographs have been taken under varying conditions of gas pressure (from 100 to 500 μ Hg of deuterium gas) and of initial longitudinal magnetic field (from zero to 3000 gauss). Some of these photographs were included in Reference 1. The MHD turbulence studies are made principally with tiny magnetic probes, and during the previous six-month period extensive studies had also been made with single probes to determine how the magnetic field fluctuations varied with differences in initial magnetic field strength, gas pressure, and location of

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*Strictly speaking, the apparatus was constructed when the Physical Research Laboratory was still a part of Space Technology Laboratories, Inc. The apparatus and personnel were subsequently transferred to the Aerospace Corporation.

probe. Toward the end of the previous reporting period, correlation studies of the signals from two probes had begun. From single probes it is possible to learn the amplitude of the fluctuations, but two probes must be used to determine the size of the turbulent eddies.

II. IMPROVEMENTS IN EQUIPMENT

The present apparatus is essentially the same as that described in Reference 1. Some improvements have been made in the measuring equipment which have in turn improved the quality of the data. The frequency response of the probes and integrators has been increased, a new type of high-pass filter has been designed, and steps have been taken to speed up the rate at which the device may be fired. These improvements are explained in more detail below.

A. Magnetic Probes

The first type of magnetic probe consisted of a coil of 24 turns of No. 44 wire wound on an 0.030-in.-diam. form. This was enclosed in a stainless steel tube, thinned and slotted at the coil end, and the entire assembly was sheathed in a 3-mm OD quartz tube. A frequency response calibration disclosed that the sensitivity fell off rapidly beyond 20 Mc (see Figure 1), a phenomenon which was attributed mainly to the inductance of the coil. At 20 Mc, the inductive impedance of the coil was about the same as the characteristic impedance of the coaxial line, 50 ohms. Other factors contributing to this decrease in sensitivity were eddy current losses in the stainless steel tube, which was about 4 mils thick, and the effect of a 12-in. length of a twisted pair of wires leading from the coil to a coaxial connector at the top of the probe assembly.

In view of these difficulties a new probe design was developed in which only 10 turns were used for the probe coil. The coil was connected directly to a 50 ohm Microdot coaxial cable, and nichrome strips 1 mil thick were used for electrostatic shielding instead of the stainless steel tube. Since the probe coil was mounted at the end of a flexible coaxial cable, it was possible to make curved probes by pushing the cable and the coil into a curved quartz tube. The curved probe shapes are necessary for some of the correlation studies. A photograph of the new probes is shown in Figure 2. The curved probes have a far better frequency response with a drop in sensitivity of only 4 db at 50 Mc (see Figure 1).

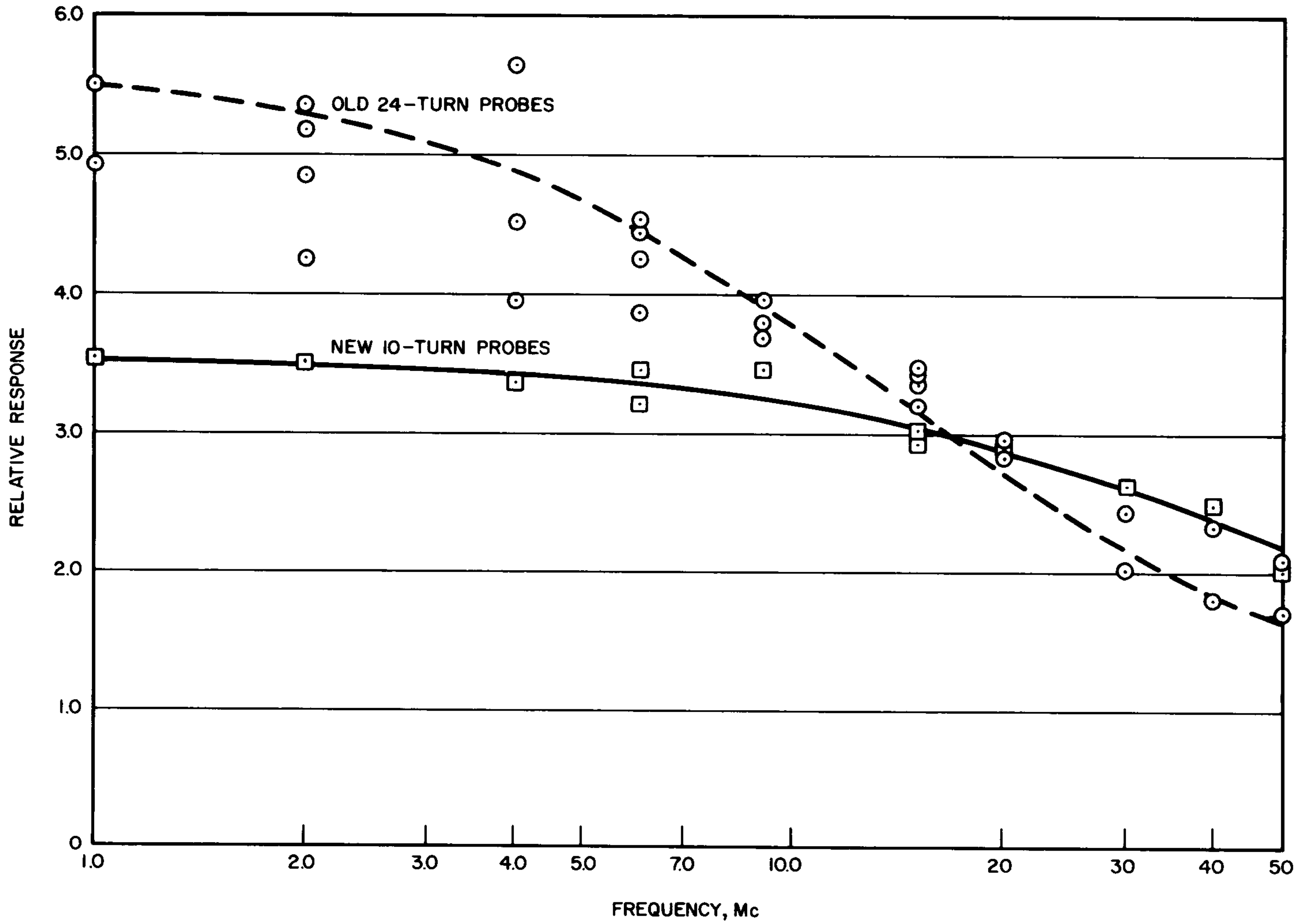

Figure 1. Frequency Response of Magnetic Probes

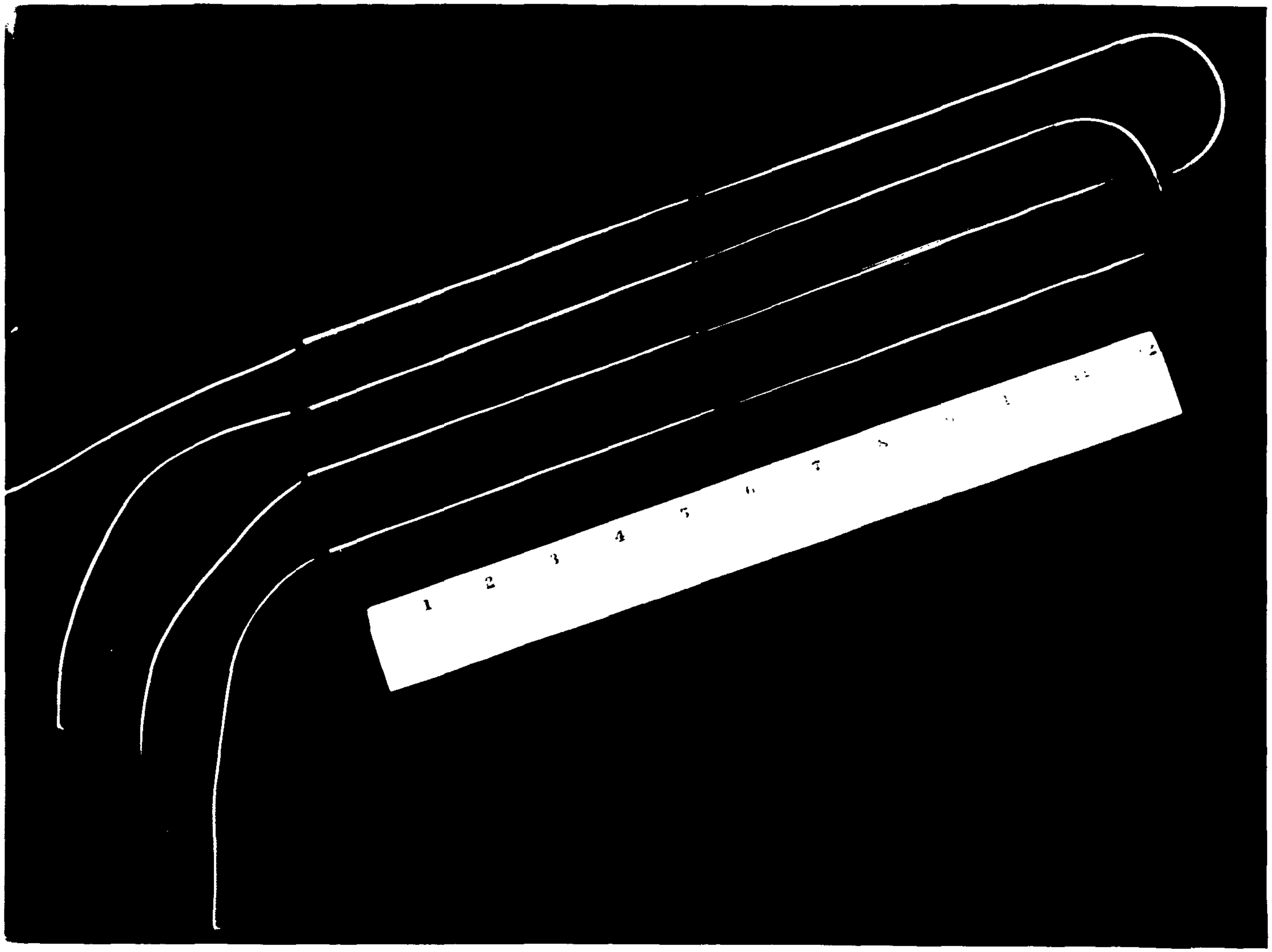

Figure 2. Photograph of New Magnetic Probes

B. Passive Integrating Circuit

Because the output signal from a magnetic probe is proportional to dB/dt, it is necessary to integrate to obtain the magnetic field, B. This is done with a conventional R-C integrating circuit. The values used were 500 ohms and 0.10 μf, giving a time constant of 50 μsec. The 0.10 μf was made up of five 0.02 μf capacitors in a radial configuration. It was discovered, however, that the inductance of the capacitor leads was sufficient to give a resonance at 22 Mc, thereby causing the integrators to operate improperly above about 12 Mc. This problem was solved by using smaller capacitors of 0.001 μf each, together with a 10 K resistor to keep the same value of RC. This increases the resonant frequency by a factor of 4 so that the new integrators are good to 50 Mc.

C. High-Pass Filters

In order to study the fluctuations of the magnetic field due to turbulence, it is necessary to discard that part of the probe signal caused by the gross motions of the plasma. In particular the diameter of the plasma column oscillates with a frequency of from 1-2 Mc. In order to eliminate this part of the signal, a high-pass filter of the M-derived type shown in Figure 3 is used. This filter cuts off very rapidly at 2 Mc, but it introduces large phase shifts and has a resonance at 2.3 Mc. For this reason the results obtained using this filter are somewhat open to question. Therefore an R-C filter with a low Q-frequency trap has been devised which, although it does not cut off as rapidly as the high-pass filter, is free of objectionable resonances. The circuit for this filter, together with its frequency response, is shown in Figure 4. So far this filter has not been used with the magnetic probes.

D. Automation

A series of 24 shots is usually required to produce one data point of correlation vs probe separation distance, and a series of approximately 50 shots would be preferable. After each shot the discharge tube must be evacuated for a period of approximately 30 seconds to remove the impurities that have been

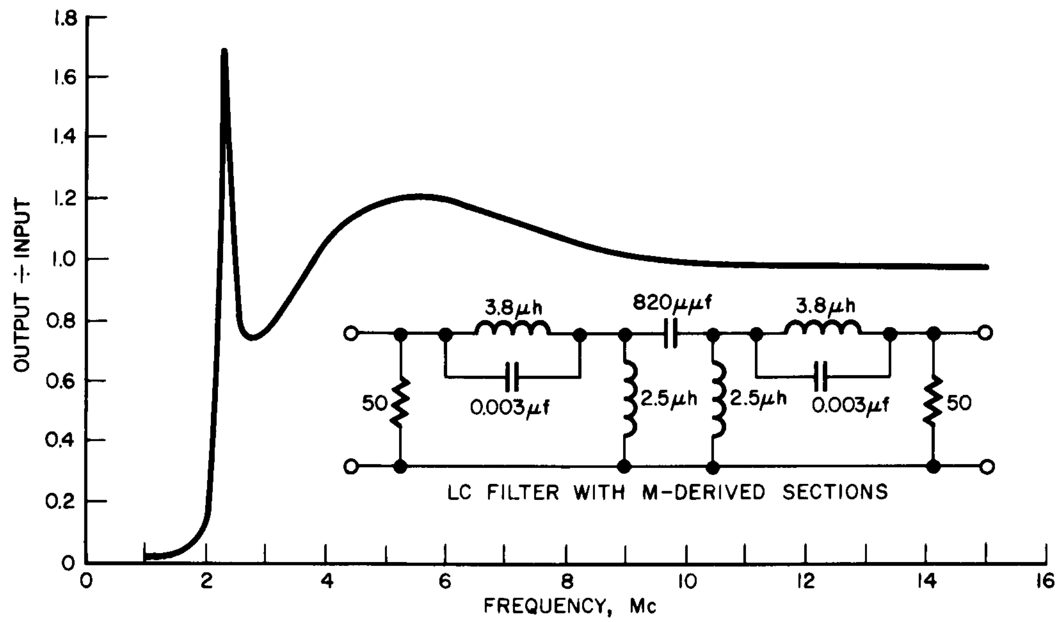

Figure 3. Frequency Response of LC High-Pass Filter

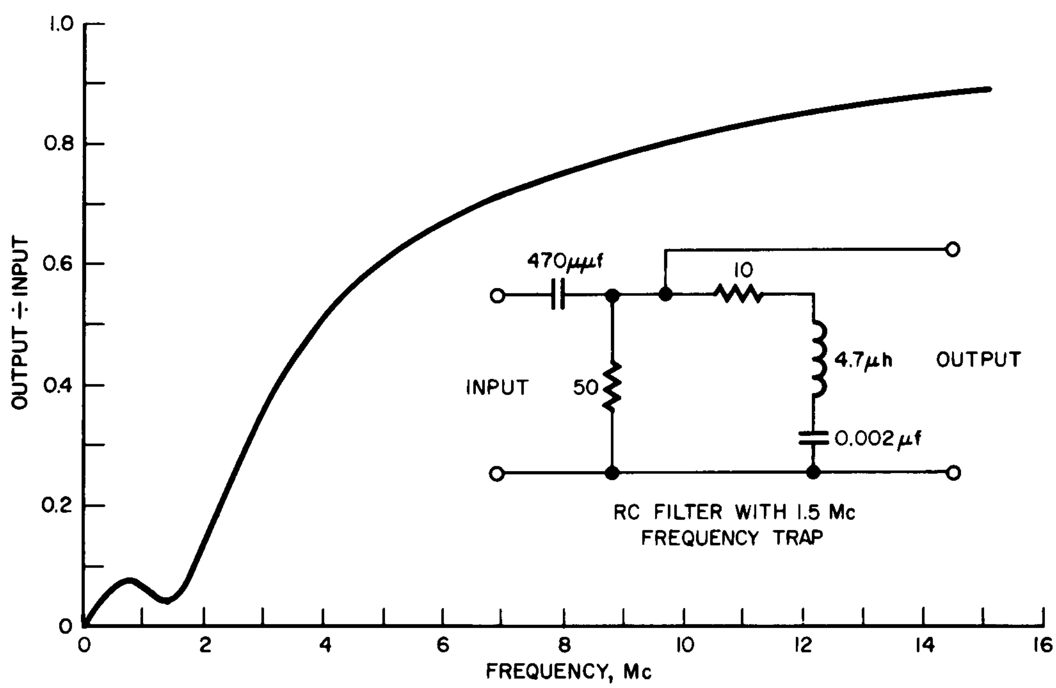

Figure 4. Frequency Response of RC High-Pass Filter with 1.5 Mc Frequency Trap

boiled off the walls. Then deuterium must be re-admitted to the tube, and the capacitor banks must be charged to exactly the correct voltage. The oscilloscope cameras must then be reset before the tube can be fired again. To perform these operations manually is extremely time-consuming. To speed up the acquisition of data it is therefore necessary either to simplify many of these operations or to make them completely automatic. So far, relay meters have been installed which shut off the power when the voltage reaches a pre-set value, and a pneumatically actuated, remotely controlled vacuum valve has been purchased but has not yet been installed. A vacuum system with a much faster pumping speed has been proposed in the new budget. Eventually all operations will be controlled from a simple console with remote reading meters. This should reduce the time of operation to one-half.

III. EXPERIMENTAL RESULTS

A. Photographic Autocorrelation

It is mentioned in Reference 1 that Kerr cell photographs had been taken of the "unstabilized" pinch. Three such photographs are shown in Figure 5. A statistical study of these instabilities can be made with a photographic autocorrelation device described by Uberoi and Kovásznay (Ref. 4). A schematic diagram of this device is shown in Figure 6. Lantern slide plates with a high contrast positive image are used. The plates have a black background with a transparent image area through which light is transmitted. The upper plate is moved at a constant rate by a small motor while the chart recorder records the output of the photocell. The output is proportional to the autocorrelation plus an additive constant.

During the previous six-month period some preliminary results were obtained with an apparatus borrowed from Prof. Kovásznay. Subsequently a photographic autocorrelation device was built specifically for the present experiment, and chart traces have been obtained of the autocorrelation vs distance of longitudinal displacement. A typical chart recording, which corresponds to the first Kerr cell photograph of Figure 5, is shown in Figure 7. There is an obvious periodicity in the chart trace indicating a predominant wavelength of the instabilities in the pinch. Using the ratio of object-to-image size, this wavelength is 1.3 cm in the pinch column.

B. x-y Correlation Patterns

In Reference 1 a technique is described whereby an x-y oscilloscope can be used to determine the correlation between two signals. Application of this technique to the actual magnetic probe signals had just begun at the end of the previous six-month period. At present, however, many x-y correlation patterns as a function of probe separation have been obtained. These will be described later.

In order to estimate the degree of correlation between two magnetic probe signals it has proven helpful to make up calibration patterns of known

Figure 5. Kerr Cell Photographs of "Unstabilized" Pinch
Delay times: 3.2, 3.6, 4.0 μsec Deuterium gas pressure: 500μ Hg
Capacitor voltage: 15 kv

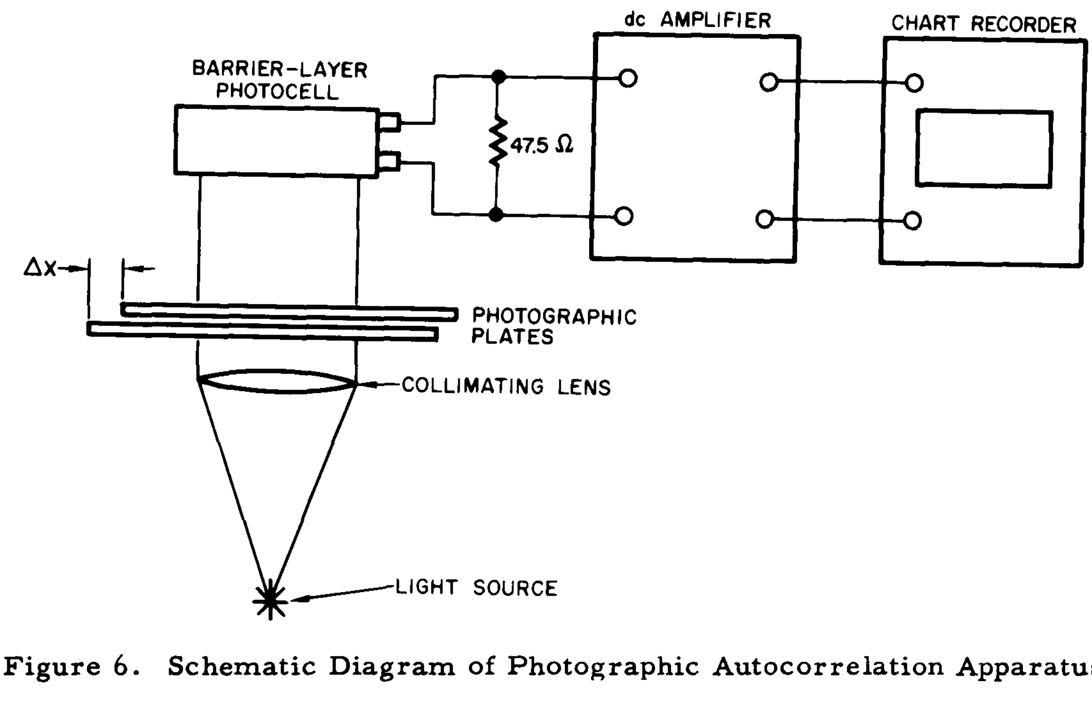

Figure 6. Schematic Diagram of Photographic Autocorrelation Apparatus

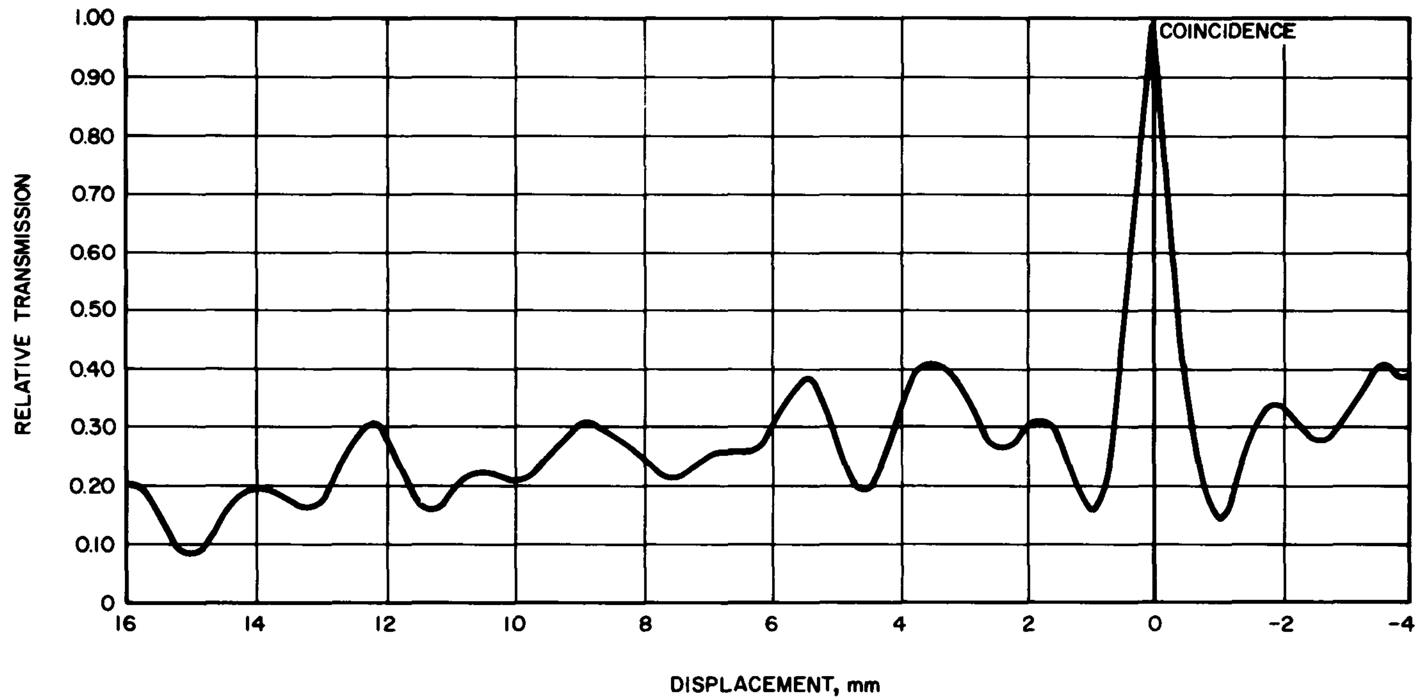

Figure 7. Photographic Autocorrelation Curve of Kerr Cell Picture (Left-hand picture shown in Figure 5)

correlation. To do this two noise generators are required. Let the signal from one noise generator be f(t) and the signal from the other be g(t). Let

$$\overline{f^2(t)} = \overline{g^2(t)} \quad \text{and} \quad \overline{f(t)g(t)} = 0 \tag{1}$$

where the bar represents a time average. Now form two new signals, F(t) and G(t), where

$$F(t) = f(t) + ag(t) \tag{2}$$

and

$$G(t) = f(t) - ag(t) \tag{3}$$

The factor a can vary between zero and unity. In practice this is controlled by a variable attenuator. The correlation, R, between the two new signals is, by definition,

$$R = \frac{\overline{F(t)G(t)}}{\sqrt{\overline{F^2(t)}\ \overline{G^2(t)}}} \tag{4}$$

Substituting for F(t) and G(t) gives

$$R = \frac{\overline{f^2(t)} - a^2\overline{g^2(t)}}{\sqrt{[\overline{f^2(t)} + a^2\overline{g^2(t)}][\overline{f^2(t)} + a^2\overline{g^2(t)}]}} = \frac{1 - a^2}{1 + a^2} \tag{5}$$

Thus any R from zero to 1 can be obtained by varying a between 1 and zero. A series of x-y oscilloscope patterns obtained in this manner are shown in Figure 8.

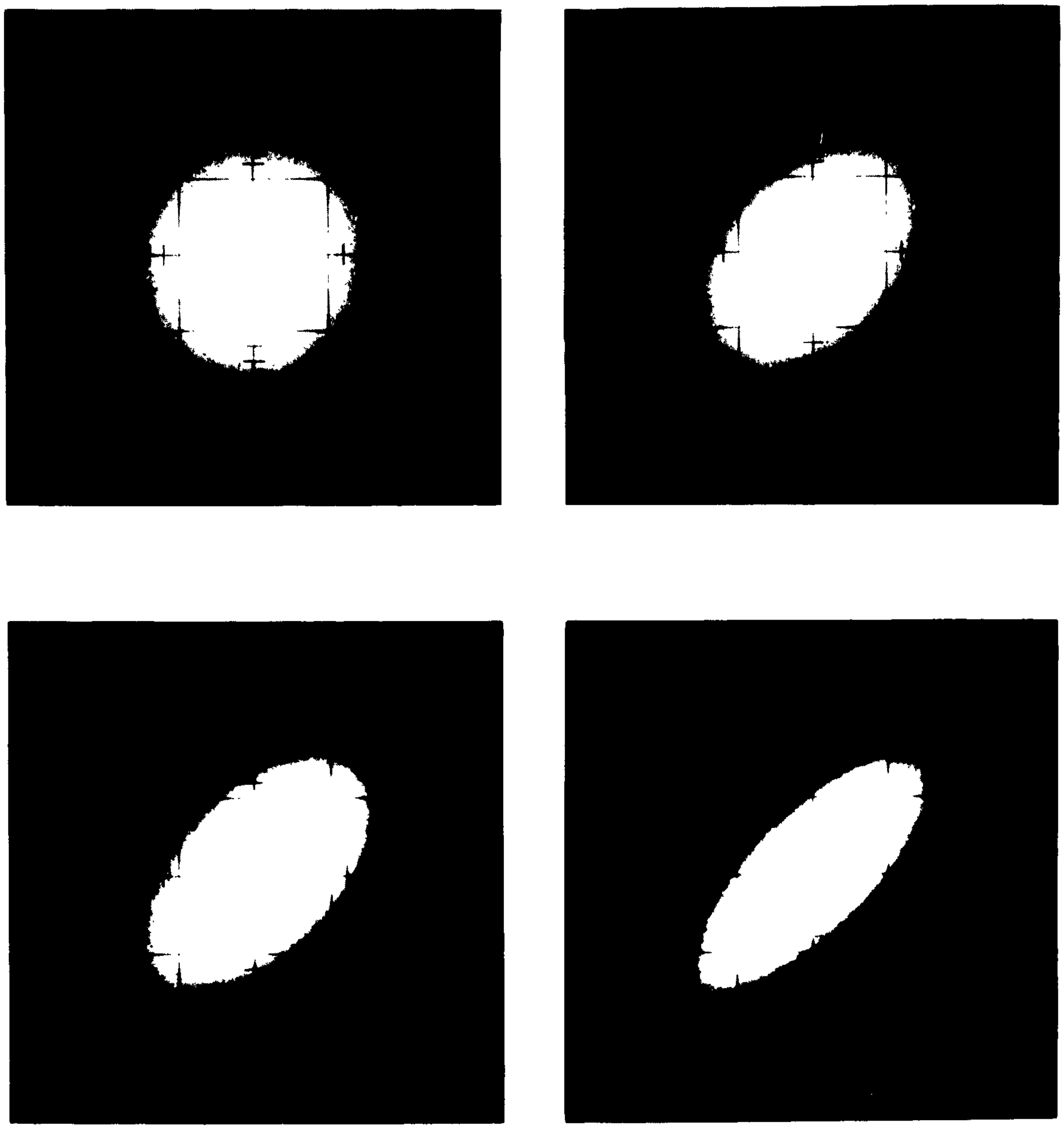

Figure 8. x-y Oscilloscope Calibration Patterns Obtained Using Noise Signals with Accurately Known Correlation

Degrees of correlation: 0%, 25%, 50%, 75%

To obtain reasonably smooth x-y correlation patterns of magnetic probe signals requires a large number of shots (usually 24 are used). A 65-volt positive gate signal is applied to the unblanking terminal of the x-y oscilloscope during the period of time that the plasma exhibits MHD turbulence. This starts at about 2.5 μsec and stops at 6 μsec when the plasma column begins breaking up because of helical instability. Thus the x-y trace is recorded only during the period of MHD turbulence. High-pass filters are used to eliminate any effect due to the gross motions of the plasma column (particularly the "breathing" mode which has a frequency of 1-2 Mc).

So far, x-y correlation patterns have been obtained from two B_z probes with varying diametrical and longitudinal separations. A series of four such x-y oscilloscope pictures using B_z probes with a diametrical separation are shown in Figure 9. The probes were placed equal distances from the tube axis and on opposite sides. At a spacing of 0.5 in., the correlation is very high (estimated at about 0.9); at 0.75 in., the correlation falls to about 0.7; and at 1.00 in., it is less than 0.5. Almost no correlation exists at a spacing of 1.5 in.

In principle it is possible to obtain the energy spectrum E(k) of the turbulence as a function of a wave number, k, by taking a Fourier transform of the correlation function. To get a reasonably good curve for E(k), however, many more points should be obtained for correlation vs separation, and the correlation must be obtained by a more accurate method than visual estimation. Several schemes are under consideration for determining quantitative correlations from the x-y oscilloscope pictures.

C. Alfvén Wave Propagation

Correlation patterns obtained with a z-separation* of B_z probes proved to be very interesting. The x-y oscilloscope patterns were quite elliptical in shape, and x-y oscilloscope photographs obtained for single shots showed elliptical traces which appeared to be sections of Lissajous patterns. This suggested that the turbulent magnetic field fluctuations were being propagated

*The z direction is defined as that parallel to the tube axis.

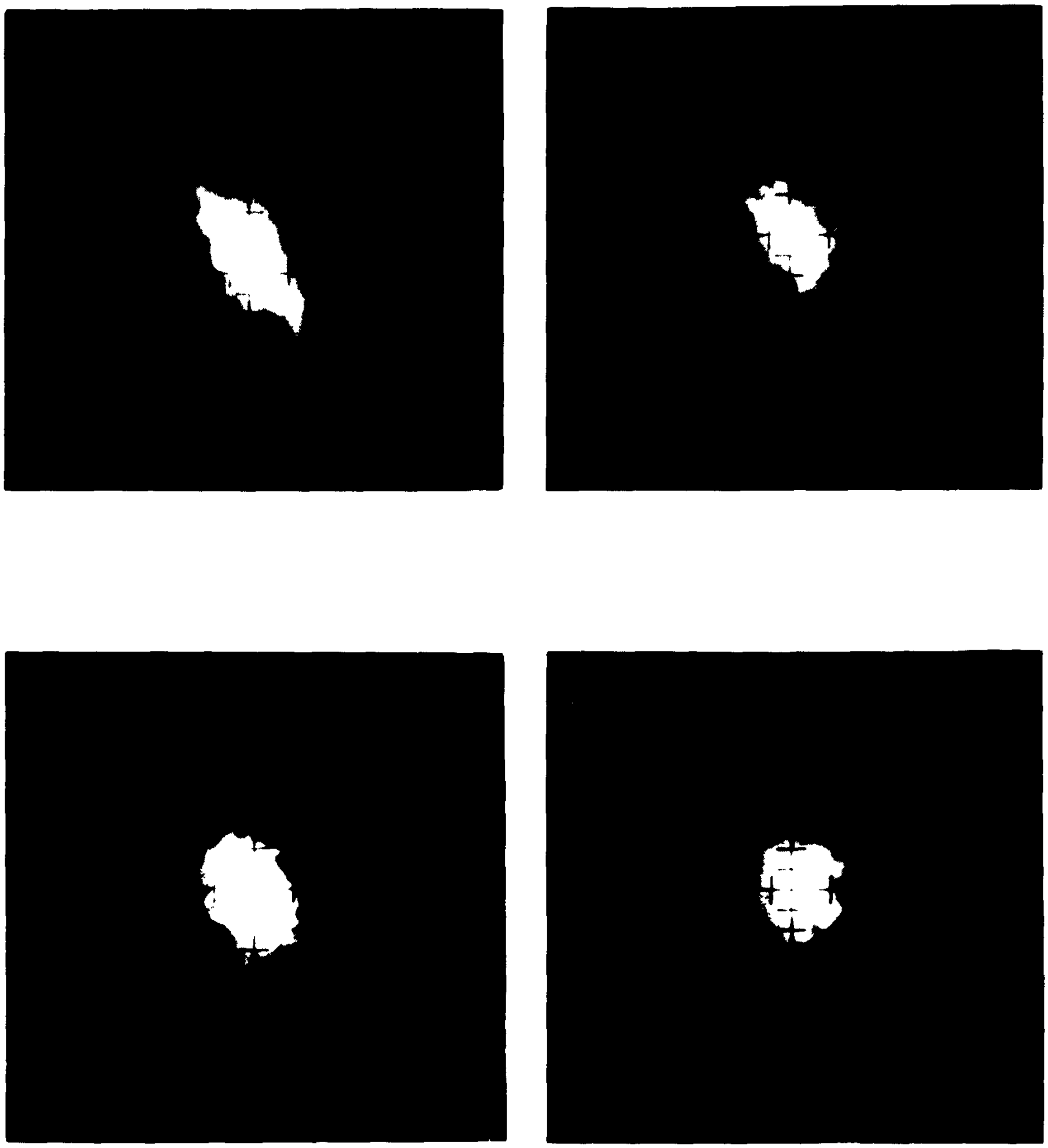

Figure 9. x-y Oscilloscope Patterns of B_z Magnetic Field

Diametrical probe separations: 0.50, 0.75, 1.00, 1.50

in the z direction with a definite velocity. This effect is not too surprising, since it is known that Alfvén waves travel along magnetic field lines, and since there is a large B_z magnetic field trapped inside the plasma column. Alfvén wave velocity is given in MKS units by

$$v_A = \frac{B}{\sqrt{\mu_o \rho}} \quad , \tag{6}$$

where B is the magnetic field strength, ρ is the plasma density, and μ_o is the permeability of free space. The Alfvén wave velocity was computed from the above formula using a measured value of B and a value of ρ calculated under the assumption that all the gas in the discharge tube is swept into the central column. This value was only one-half the velocity indicated by the Lissajous patterns, however. One must therefore consider the possibility that much of the gas is left behind as the current sheath pinches inward, so that the gas density is somewhat lower than assumed.

D. rms Values of B, $\dot{B}$, and $\ddot{B}$

A preliminary analysis has been made of some recent data in an effort to estimate the magnitude of the random fluctuations. Measurements have been made of B_z, B_r, and B_θ, using the integrated probe signals; of $\dot{B}_z$, $\dot{B}_r$, and $\dot{B}_\theta$, using the direct probe signals; and of $\ddot{B}_z$, $\ddot{B}_r$, and $\ddot{B}_\theta$, using an RC differentiating circuit. The results of this analysis show that the magnitude of the fluctuations in the three perpendicular directions are about equal within a factor of 2. The magnitudes are roughly as follows:

$$(\Delta B)_{rms} = 200 \text{ gauss}$$

$$(\Delta \dot{B})_{rms} = 5 \times 10^9 \text{ gauss/sec}$$

$$(\Delta \ddot{B})_{rms} = 1.5 \times 10^{17} \text{ gauss/sec}^2$$

These values are probably accurate within a factor of 2 since they are only visual estimates. For reference the value of B_z is about 16,000 gauss.

It is useful to form the following nondimensional quantity:

$$\frac{(\Delta B)(\Delta \ddot{B})}{(\Delta \dot{B})^2} \quad .$$

This quantity can not be less than unity. For a pure sine wave it is unity, and for random noise with a gaussian distribution it is $\sqrt{3}$. For present values, this quantity is slightly greater than unity.

A study has also been made to find the highest frequencies present in the MHD turbulence, i. e. , the high frequency cutoff of the energy spectrum. The low frequencies were reduced to a small value by using an RC differentiating circuit. The resulting $\ddot{B}$ signals were displayed on a Tektronix 517 oscilloscope, which has a frequency response of greater than 50 Mc at a fast sweep speed. Frequencies of up to 20 Mc were observed. The ion cyclotron frequency is about 12 Mc, so the high frequency cutoff is almost twice the ion cyclotron frequency. The ion cyclotron frequency therefore appears to have no effect on the maximum frequency of MHD turbulence.

E. Kerr Cell Photographs in Color

Nitrobenzene, the liquid usually used for Kerr cells, absorbs strongly in the blue end of the spectrum so Kerr cell photography was limited to black and white. Recently, however, the laboratory acquired a Kerr cell with a clear liquid which transmits down to 2500Å. The Kerr constant is somewhat less than that of nitrobenzene so the aperture of the cell was small—only 0.2 x 0.4 in. If the Kerr cell is made a field stop, however, it is possible to use the large lens aperture required for the slower color film. An objective lens was used to form an image of the pinch tube inside the Kerr cell, and a relay lens formed this image onto 35mm Super Anscochrome color film. The exposure was quite adequate, and the resolution was excellent. Color photography is often useful in the study of high temperature plasmas, as the color of the emitted light can be used to estimate relative temperatures of different regions and to indicate the presence of impurities.

IV. FUTURE REQUIREMENTS

Data acquired up to the present have been of a more or less qualitative nature, and have led to a good understanding of the phenomena under study. A great deal of effort has gone into the development of reliable instrumentation—in particular, the magnetic probes—and it is now desirable that the data reduction be made more quantitative. Techniques should now be developed for determining correlation values from the x-y oscilloscope pictures and from the oscilloscope traces of the magnetic probe signals themselves. Several techniques have been considered for quantitatively determining the correlation from the x-y oscilloscope pictures, but none has been tested so far. It would be preferable to determine such quantities as the correlation, rms values, etcetera, from measurements of the oscilloscope photographs of the probe signals themselves. However, the detailed measurements of many oscilloscope traces plus the extensive calculations required to determine the correlation would require far more time than is feasible. One way to overcome this difficulty is to use automatic data reduction methods. A method whereby photographs of oscilloscope traces could be measured automatically and the readings punched on paper tape is under consideration. The data on the paper tape could then be easily converted into a form suitable for processing on a digital computer. This method appears very attractive, but, to the author's knowledge, there is not yet available a device for automatically reading data from an oscilloscope photograph.

V. SUMMARY

A stabilized linear pinch device is being used in order to study MHD turbulence. This device is similar to the Columbus S-4 device at Los Alamos in which Lovberg and Burkhardt (Ref. 2) found the random flucturations in the magnetic field which Kovásznay (Ref. 3) attributed to turbulence. A description of the apparatus used for the present experiment is given in Reference 1.

In the past six-month period, several improvements have been made in the measuring instruments. New magnetic probes with a frequency response of greater than 50 Mc are now in use. Because the old RC integrators which convert the $\dot{B}$ probe signal to B were found to operate properly to only 12 Mc, new integrators were built which operate to over 50 Mc. An extensive study has been made of the high-pass filters which eliminate low-frequency signals caused by the gross motion of the plasma. The LC filters have been replaced with RC filters with a frequency trap at 1.5 Mc to eliminate the frequency due to radial oscillations of the column. Efforts have been made to speed up the shooting cycle of the device and so far relay meters have been put on the high voltage supplies which shut them off when the capacitor banks are charged to pre-set voltages. An operating console with control switches and remote reading meters has also been built. A pneumatically operated vacuum valve and a faster vacuum system will be installed in the future.

During the past six-month period an autocorrelation analysis has been made of some Kerr cell photographs to determine statistically the wavelengths associated with the instabilities of the pinch column. The x-y oscilloscope correlation method has been used to determine the degree of correlation between two magnetic probe signals as a function of their separation. Very promising results have been achieved for the two configurations used: a diametrical separation of B_z probes and a z-separation of B_z probes. For the latter, clear evidence was found of Alfvén wave propagation of the turbulent eddies along the lines of magnetic field. The rms values of the magnetic field fluctuations were estimated to within a factor of 2, and a fair degree of isotropy was found. Studies were made of the $\ddot{B}$ signals in which the maximum frequency of the turbulence was determined to be about 20 Mc—almost twice the ion cyclotron frequency.

A new Kerr cell which transmits the entire visible spectrum was used to obtain high fidelity color photographs of the pinched plasma with an exposure duration of only 0.1 μsec.

Much thought has been given to the need for reducing the data to a quantitative form. The study of turbulence, by its very nature, requires large quantities of data for statistical averaging. Manual measurements and calculations would require far too much time, so it appears that automatic film measurement and calculation by a digital computer must be used.

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Aerospace Corporation, El Segundo, California. EXPERIMENTAL MAGNETOHYDRODYNAMIC TURBULENCE INVESTIGATIONS, by E. B. Turner. 16 August 1962. [25]p. incl. illus. (Report TDR-69(2230-14)TR-1;DCAS-TDR-62-167) (Contract AF 04(695)-69) Unclassified report

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